

Dark Matter collisions with the Human Body

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We investigate the interactions of Weakly Interacting Massive Particles (WIMPs) with nuclei in the human body. We are motivated by the fact that WIMPs are excellent candidates for the dark matter in the Universe. Our estimates use a 70 kg human and a variety of WIMP masses and cross-sections. The contributions from individual elements in the body are presented and it is found that the dominant contribution is from scattering off of oxygen (hydrogen) nuclei for the spin-independent (spin-dependent) interactions. For the case of 60 GeV WIMPs, we find that, of the billions of WIMPs passing through a human body per second, roughly ~ 10 WIMPs hit one of the nuclei in the human body in an average year, if the scattering is at the maximum consistent with current bounds on WIMP interactions. We also study the 10–20 GeV WIMPs with much larger cross-sections that best fit the DAMA, COSENT, and CRESST data sets and find much higher rates: in this case as many as 10^5 WIMPs hit a nucleus in the human body in an average year, corresponding to almost one a minute. Though WIMP interactions are a source of radiation in the body, the annual exposure is negligible compared to that from other natural sources (including radon and cosmic rays), and the WIMP collisions are harmless to humans.

A variety of astrophysical observations has shown conclusively that the majority of the matter in the Universe consists of an unknown nonluminous, nonbaryonic component. Understanding the nature of this dark matter is one of the major outstanding problems of astrophysics and particle physics. Most cosmologists believe that the solution to this puzzle lies in the discovery of a new type of fundamental particle. Leading candidates for the dark matter are Weakly Interacting Massive Particles (WIMPs), a generic class of particles that are electrically neutral and do not participate in strong interactions, yet have weak interactions with ordinary matter. Possible WIMP candidates include supersymmetric particles and Kaluza-Klein particles motivated by theories with extra dimensions. These particles are thought to have masses in the range 1 GeV–10 TeV, consistent with their being part of an electroweak theory.

Searches for WIMPs [1–3] include direct detection laboratory experiments, which look for the elastic scattering of WIMPs in the Galaxy as they pass through terrestrial detectors situated in deep underground sites. These efforts are ongoing worldwide. Currently there are intriguing hints of discovery with the DAMA [4], CoGeNT [5, 6], and CRESST [7] experiments although no consensus has been reached in the community. The null results of

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a host of other experiments, including CDMS [8] and XENON [9, 10] have been used to place bounds on the scattering rates of WIMPs as a function of WIMP mass. In the standard framework used in this work, there is a strong tension between the results of the first three experiments and the null results of the latter two. Many efforts in both the experimental and theoretical directions are ongoing to understand these discrepancies; in this paper we will simply use the currently published results of these experiments.

In this paper we consider this same elastic scattering of WIMPs with nuclei in the human body. Billions of WIMPs pass through our bodies every second, yet most of them pass through unimpeded. Only rarely does WIMP actually hit one of our nuclei. To perform our analysis we will assume a human of 70 kg and consider a variety of WIMP masses in the GeV–TeV range. First we will study 60 GeV WIMPs with the maximum scattering cross-section allowed by the null results of the XENON and CDMS experiments. Then we will turn to the lower mass WIMPs (10–20 GeV) that provide the best fits to the hints of discovery in DAMA, CRESST, and COGENT as well as TeV benchmark cases again compatible with the null result experiments. Finally, we examine the radiation exposure these interactions represent and how it compares to other natural radiation sources.

The scattering rate of WIMPs with an element (indexed by k) in a human body of mass M_{body} is given by¹

$$R_k = N_k n_\chi \langle v \sigma_k \rangle = \left(\frac{f_k M_{\text{body}}}{m_k} \right) \left(\frac{\rho_\chi}{m_\chi} \right) \int d^3v v f(\mathbf{v}) \sigma_k(v), \quad (1)$$

where $N_k = \frac{f_k M_{\text{body}}}{m_k}$ is the number of nuclei of that element in the body, with m_k the nuclear mass and f_k the mass fraction of that element; $n_\chi = \frac{\rho_\chi}{m_\chi}$ is the number density of WIMPs, with m_χ the WIMP mass and ρ_χ the local dark matter mass density; $f(\mathbf{v})$ is the WIMP velocity distribution; and $\sigma_k(v)$ is the (velocity-dependent) WIMP-nucleus scattering cross-section.

To a reasonable first approximation, the dark matter halo can be treated as a non-rotating, isothermal sphere (the Standard Halo Model) [2, 3]. For the resulting Maxwellian velocity distribution, a 3D velocity dispersion of 270 km/s is assumed. The velocity distribution is truncated at 550 km/s to account for the fact that high velocity particles would escape the galaxy [11], though the results of this paper are fairly insensitive to this cutoff as such high velocity particles would otherwise make only a small contribution to the *total* scattering rate². The local density of the dark matter halo is taken to be 0.4 GeV/cm³. While the smooth halo component is likely to be supplemented by a variety of substructures such as streams, clumps, or debris flow, their contributions are unlikely to be large enough to substantially modify the results of this paper.

Dropping the isotope index k , the scattering cross-section is given by

$$\sigma(v) = \int_0^{q_{\text{max}}^2} dq^2 \frac{d\sigma}{dq^2}(q^2, v), \quad (2)$$

¹ The rate here is a pure rate, not a rate per unit target mass as is commonly used in the dark matter direct detection literature.

² The same cannot always be said for the rates in direct detection experiments as these experiments are sensitive to events that produce energies above a threshold, not the total number of events. In some cases, only high velocity WIMPs produce scattering events above threshold, so the choice of cutoff becomes important.

where q is the momentum transferred in a scatter, $q_{\max} = 2\mu v$ is the maximum momentum transfer in a scatter at a relative velocity v , μ is the WIMP-nucleus reduced mass, and

$$\frac{d\sigma}{dq^2}(q^2, v) = \frac{\sigma_0}{4\mu^2 v^2} F^2(q) \Theta(q_{\max} - q), \quad (3)$$

with Θ the step function and σ_0 the scattering cross-section in the zero-momentum-transfer limit. Here, $F^2(q)$ is a form factor to account for the finite size of the nucleus. For small momentum transfers, the WIMP coherently scatters off the entire nucleus; the nucleus is essentially a point particle in this case, with $F^2(q) \rightarrow 1$. For sufficiently small v , such that the possible momentum transfer remains small, $\sigma(v) \rightarrow \sigma_0$. As the de Broglie wavelength of the momentum transfer becomes comparable to the size of the nucleus, the interaction becomes sensitive to the spatial structure of the nucleus and $F^2(q) < 1$, with $F^2(q) \ll 1$ at higher momentum transfers. For velocities at which this form factor becomes relevant, $\sigma(v) < \sigma_0$ (with $\sigma(v) \ll \sigma_0$ at very high velocities). The velocity at which this form factor causes the cross-section $\sigma(v)$ to start to significantly deviate from the zero-momentum-transfer limit σ_0 is dependent on the nuclei in question for two reasons: (1) the size of the nucleus grows as the nucleus gets heavier and (2) the momentum transferred becomes larger as the nucleus gets heavier, assuming the WIMP is heavier than the nuclei in question. For the typical WIMP velocities in the halo, the form factor suppression is negligible for nuclei much lighter than iron ($\sigma(v) \approx \sigma_0$), while it is significant for nuclei much heavier³.

There are two types of interactions commonly considered for WIMP scattering: spin-independent (SI) and spin-dependent (SD). Each coupling has its own form factor and Eqn. (1) must be summed over these two contributions. In the SI case, the WIMP essentially couples to the mass in the nucleus, with a zero-momentum-transfer limit cross-section

$$\sigma_{0,\text{SI}} = \frac{4\mu^2}{\pi} [Zf_p + (A - Z)f_n]^2, \quad (4)$$

where f_p and f_n are the couplings to the proton and neutron, respectively, Z is the number of protons in the nucleus, and $A - Z$ is the number of neutrons. For many WIMP candidates, $f_p \approx f_n$ and the cross-section scales as

$$\sigma_{0,\text{SI}} = \frac{\mu^2}{\mu_p^2} A^2 \sigma_{p,\text{SI}}, \quad (5)$$

where μ_p is the WIMP-proton reduced mass and $\sigma_{p,\text{SI}}$ is the SI WIMP-proton scattering cross-section. We will assume $f_p = f_n$ below, though the results are only very mildly sensitive to the ratio of these two couplings except in the case $\frac{f_p}{f_n} \approx -\frac{A-Z}{Z}$ where the terms in Eqn. (4) cancel.

In the SD case, as the name implies, the WIMP couples to the spin of the nucleus, with

$$\sigma_{0,\text{SD}} = \frac{32\mu^2}{\pi} G_F^2 J(J+1) \Lambda^2, \quad (6)$$

³ For the same reasons as given in the previous footnote (the application of a threshold), the form factor is more important for direct detection and it can significantly suppress the direct detection rates above threshold even when the total rate does is not significantly affected.

Element	Mass	Rates [yr ⁻¹]	
	Fraction	SI	SD
Oxygen	0.61	3.49	0.25
Carbon	0.23	0.63	0.64
Hydrogen	0.10	0.00023	22.5
Nitrogen	0.026	0.11	0.0097 [†]
Calcium	0.014	0.64	0.011
Phosphorus	0.011	0.30	5.7
Potassium	0.0020	0.089	0.27
Sulfur	0.0020	0.059	0.0027
Sodium	0.0014	0.019	0.58
Chlorine	0.0012	0.043	0.079
Magnesium	0.00027	0.0043	0.024
Silicon	0.00026	0.0057	0.0023
Iron	0.00006	0.0050	0.00001
<i>Total</i>	1.00	5.39	30.1

TABLE I: Interactions of 60 GeV WIMPs on various nuclei in the human body. The mass fraction of the most significant elements in the human body, taken from Ref. [18] (which in turn refers to Refs. [19, 20]), is shown. Also shown are the number of WIMP scatters per year for each element at the largest spin-independent (SI) and spin-dependent (SD) scattering cross-sections not currently excluded by XENON100 [10], which are $\sigma_{\text{p,SI}} = 10^{-8}$ pb and $\sigma_{\text{p,SD}} = 2 \times 10^{-3}$ pb, respectively. We assume a human mass of 70 kg and identical couplings to the proton and neutron. (†) The SD rate for nitrogen-14 has not been calculated but may be non-negligible and perhaps as large as $\mathcal{O}(10)$; see the text.

where J is the spin of the nucleus,

$$\Lambda \equiv \frac{1}{J} (a_{\text{p}} \langle S_{\text{p}} \rangle + a_{\text{n}} \langle S_{\text{n}} \rangle) , \quad (7)$$

a_{p} and a_{n} are the couplings to the proton and neutron, respectively, and $\langle S_{\text{p}} \rangle$ and $\langle S_{\text{n}} \rangle$ are the spin contributions from the proton and neutron groups, respectively. In our analysis, we shall assume identical couplings to the proton and neutron ($a_{\text{p}} = a_{\text{n}}$), so that

$$\sigma_{0,\text{SD}} = \frac{\mu^2 J(J+1)}{\mu_{\text{p}}^2 \frac{1}{2}(\frac{1}{2}+1)} \left(\frac{\langle S_{\text{p}} \rangle + \langle S_{\text{n}} \rangle}{J} \right)^2 \sigma_{\text{p,SD}} . \quad (8)$$

Whereas the couplings to neutrons and protons are roughly identical for SI scattering for many WIMP candidates, in the case of SD scattering they may differ. Typically, however, the two SD couplings are found to be within a factor of 2–3 of each other. Our results, using identical couplings, will thus be order of magnitude estimates of the general case.

More detailed discussions of dark matter scattering kinematics, cross-sections, and form factors can be found in Refs. [12–15]; other reviews can be found in Refs. [16, 17].

Table I shows the mass fractions of the most significant elements in the human body as well as the scattering rates for each element for a 70 kg body and a 60 GeV WIMP. Rates are

shown for both SI and SD scattering, assuming scattering cross-sections of $\sigma_{\text{p,SI}} = 10^{-8}$ pb and $\sigma_{\text{p,SD}} = 2 \times 10^{-3}$ pb, respectively, the largest cross-sections not excluded by XENON at that WIMP mass. Oxygen and carbon are the largest components in the human body by mass and also contribute the most to the SI scattering rate, with oxygen accounting for 65% of the SI scatters at this WIMP mass. However, hydrogen, the largest component by number of atoms (representing about 60% of the atoms in the human body), has a much smaller SI scattering rate than many other elements with significantly smaller mass fractions (as well as number of atoms). For example, iron, while accounting for less than 1/1000 the mass of the hydrogen, nevertheless has an SI scattering rate ~ 20 times larger. The reason for this lies in the scaling of the SI cross-section shown in Eqn. (5). In addition to the explicit A^2 factor, the $\frac{\mu^2}{\mu_{\text{p}}^2}$ factor also scales as A^2 (for nuclei much lighter than the WIMP), so that the cross-section scales as A^4 . For a given mass fraction, the number of nuclei is proportional to $1/A$, so the interaction rate scales as A^3 . With this scaling and the mass fractions shown in the table, the relative oxygen-to-hydrogen SI scattering rate should then approximately be $\frac{0.61}{0.10} \left(\frac{16}{1}\right)^3 \approx 25,000$, in reasonable agreement with the actual value of $\frac{3.49}{0.00023} \approx 15,000$; the overestimate in the first case is due to the fact that $\frac{\mu^2}{\mu_{\text{p}}^2} \rightarrow A^2$ applies in the limit that the WIMP is much heavier than the nucleus, a limit that has not been fully reached here. As the nuclei become heavier, the form factor becomes more and more significant, so the A^3 scaling in the interaction rate for a given mass fraction no longer holds, though the rate still grows rapidly.

On the other hand, scattering with hydrogen is the dominant contribution in the SD case. The primary difference is that, unlike the SI case, there is no explicit A^2 scaling in the scattering cross-section: the spin factors in Eqn. (8) are of $\mathcal{O}(1)$ for all nuclei. With the μ^2 factor, the SD cross-section scales as $\sim A^2$. After accounting for the $1/A$ scaling of the number of nuclei for a given mass fraction, the total scattering rate scales as $\sim A$ (neglecting form factors). However, isotopes with zero nuclear spin ($J = 0$) have $\sigma_{0,\text{SD}} = 0$, so they do not contribute at all to the SD scattering rate. Many of the elements listed in Table I, including oxygen and carbon, are mainly composed of spinless isotopes, with non-zero spin isotopes representing only a small fraction of that element's natural composition. The SD scattering rate is thus suppressed in these cases. Hydrogen, on the other hand, is mainly composed of spin-1/2 ^1H ; even spin-1 deuterium contributes to SD scattering. Because of the A scaling of the scattering rate for a given mass fraction and the relative isotopic compositions between spinless and non-zero spin nuclei, hydrogen dominates the SD capture rate.

In our analysis, we have neglected the SD contribution of spin-1 ^{14}N . As this is the dominant isotope of nitrogen, nitrogen is expected to have a significant SD scattering rate. However, this nucleus belongs to a small group of proton-odd, neutron-odd isotopes with non-zero spin that are not well characterized in the scattering literature and we are unaware of existing estimates for $\langle S_{\text{p}} \rangle$ and $\langle S_{\text{n}} \rangle$. Taking $|\langle S_{\text{p}} \rangle| \sim |\langle S_{\text{n}} \rangle| \sim 0.1$, similar to nearby nuclei (except one of these two quantities is nearly zero in these other nuclei), we can expect $\mathcal{O}(10)$ SD scattering events per year with nitrogen in the human body. This would make nitrogen one of the larger contributors to the total SD rate, though hydrogen still remains the dominant source of SD interactions.

The overall scattering rates of $\mathcal{O}(10)$ should not be unexpected for the benchmark WIMP mass and cross-sections here. These benchmarks would produce a few events/year in the ~ 100 kg of liquid xenon that is the target mass in the XENON experiment, the currently

Benchmark	WIMP Mass [GeV]	Cross-section [pb]	Rate [yr ⁻¹]
<i>spin-independent</i>			
CoGeNT best-fit	8.	$7. \times 10^{-5}$	6.3×10^4
CRESST M1	25.3	1.6×10^{-6}	1300
CRESST M2	11.6	3.7×10^{-5}	3.4×10^4
DAMA best-fit	11.0	2.0×10^{-4}	1.8×10^5
XENON allowed	60.	$1. \times 10^{-8}$	5.4
XENON allowed	1000.	$8. \times 10^{-8}$	3.9
<i>spin-dependent</i>			
DAMA best-fit	11.0	0.68	9.0×10^4
XENON allowed	60.	0.001	30.
XENON allowed	1000.	0.01	19.

TABLE II: The total number of scatters within a human body per year for the given WIMP masses and WIMP-proton scattering cross-sections. The CoGeNT, CRESST, and DAMA benchmarks are those that best fit the data for the respective experiments (CRESST has two maximum likelihood points); these points are all strongly disfavored by the null results of CDMS and XENON in the standard framework used in this analysis. The XENON benchmarks are compatible with the null results of CDMS and XENON. We assume a human mass of 70 kg and identical couplings to the proton and neutron.

measured event rate in the detector (though the measured rate is also consistent with backgrounds alone). With a similar mass between the human body and the XENON detector, the rates should be of similar orders of magnitude, though detection efficiencies, thresholds, and different target elements mean the rates are not simply proportional to the target mass. Since xenon ($A \approx 130$) is much heavier than oxygen ($A \approx 16$), one might expect a much higher rate in XENON than the human body for SI scattering due to the $\sim A^4$ cross-section scaling ($\sigma_{0,\text{Xe}}$ is $\mathcal{O}(10^3)$ larger than $\sigma_{0,\text{O}}$). However, due to a threshold and a $<100\%$ detection efficiency, the few events/year rate measured in XENON is not the *total* rate in the detector, which is somewhat higher (by an order of magnitude or more). In addition, xenon scattering will be form factor suppressed, so that the total scattering rate for xenon is not as high as would be expected from the A^4 scaling alone. For the SD case, the $\mathcal{O}(10)$ higher scattering rate in the human body versus the XENON experiment can be attributed to the much larger number of non-zero spin nuclei in the former case (mainly hydrogen).

In Table II, we show scattering rates in the body for several WIMP benchmarks. The benchmarks are chosen to correspond to the approximate best-fit WIMP mass and scattering cross-section for the CoGeNT [5, 6], CRESST [7], and DAMA [4] experiments. Two CRESST benchmark points are included, corresponding to the two sets of parameters that maximize their likelihood function, M1 (the global maximum) and M2 (a local maximum). While DAMA likewise has two best-fit points, we have included only the lower mass one as the higher mass point is in strong conflict with the null results of XENON [9, 10] and CDMS [8]. We note that, in fact, all of the CoGeNT, CRESST, and DAMA benchmark points are incompatible with XENON and CDMS under the analysis framework we are using here. Many researchers are trying to understand the origin of these differences; in this paper

we simply follow the published results in choosing our benchmark points. Two additional benchmark points are included, corresponding to the maximum cross-section consistent with the null results of XENON (and CDMS, which has a slightly weaker constraint) for WIMP masses of 60 GeV and 1 TeV; the former case is the benchmark used in Table I. All benchmarks are included for the SI case, while only the DAMA best-fit and XENON-allowed benchmarks are included in the SD case.

The scattering rates for the CoGeNT, CRESST, and DAMA benchmark points are all significantly larger than the rates for the XENON-allowed benchmarks, as the former are all at cross-sections higher than those that would produce the allowed few events/year observed in XENON. The rates for these positive-signal benchmarks vary from ~ 4 per day (CRESST M1) to ~ 20 per hour (DAMA, SI case). For the XENON-allowed cases, the rates are several per year in the SI case, but a moderately larger ~ 2 per month in the SD case.

At WIMP masses below 60 GeV, XENON begins to lose sensitivity: the rate above threshold becomes a smaller and smaller portion of the total rate. For low masses, one can thus choose cross-sections resulting in very large total rates (in both the human body and XENON detector), that produce only a few events above threshold and are thus not excluded by XENON.

WIMP interactions represent a source of radiation in the human body, so a question arises: are WIMP collisions dangerous to humans? Here we compare the radiation due to WIMPs with that from natural sources, namely radioactivity here on Earth (including radon) as well as cosmic rays coming down through the atmosphere. The natural radiation background varies by location, with a typical annual exposure of 0.4–4 mSv (see Refs. [21, 22] for a review; here the unit of radiation exposure is Sieverts, or Sv). The cosmic-ray contribution is 0.3 mSv/yr at sea level and increases at higher elevations. Cosmic-ray muons deposit far more energy in the human body than do WIMPs. These muons pass through the human body at a rate of a few per second, depositing ~ 10 – 100 MeV of energy each, far larger than the ~ 10 keV deposited by a WIMP. For comparison, for the XENON-allowed benchmarks we have considered, the dose-equivalent exposure due to WIMP interactions is $\mathcal{O}(10^{-11})$ mSv/yr, a negligible exposure compared to other natural radiation sources. Indeed we find that the radiation dose from cosmic-rays received each second exceeds the lifetime WIMP dose. Even for the higher WIMP interaction rates for the masses and cross-sections that can reproduce the CoGeNT, CRESST, and DAMA results, the WIMP radiation dose is negligible compared to other radiation sources. Thus WIMPs are harmless to the human body.

In conclusion, we have studied the interactions of WIMPs with nuclei in a human body of mass 70 kg. We examined the contributions from a variety of elements in the body and found that the dominant contribution is from scattering off of oxygen nuclei for spin-independent (SI) interactions and hydrogen nuclei for spin-dependent (SD) interactions. For a canonical case of 60 GeV WIMP mass and the maximum elastic scattering cross-sections compatible with the experimental bounds from XENON and CDMS ($\sigma_{p,SI} = 10^{-8}$ pb = 10^{-44} cm² and $\sigma_{p,SD} = 2 \times 10^{-3}$ pb), we found that on average five WIMPs hit one of the nuclei in the human body in a year via SI scattering and 30 via SD scattering. We also studied the 10–20 GeV WIMPs with much larger cross-sections that best fit the DAMA, COGENT, and CRESST data sets, and found much higher rates: in this case as many as 10^5 WIMPs hit a nucleus in the human body in an average year, corresponding to almost one a minute. Finally, we have determined that, while these WIMP interactions represent a source of radiation in the body, the exposure rate is negligible compared to that from other natural sources of radiation and

WIMP collisions are harmless to humans.

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